

Energy dependence of π^0 production in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4, \text{ and } 200 \text{ GeV}$

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Neutral pion transverse momentum (p_T) spectra at midrapidity ($|y| \leq 0.35$) were measured in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4$, and 200 GeV. Relative to π^0 yields in p+p collisions scaled by the number of inelastic nucleon-nucleon collisions (N_{coll}) the π^0 yields for $p_T \gtrsim 2$ GeV/c in central Cu+Cu collisions are suppressed at 62.4 and 200 GeV whereas an enhancement is observed at 22.4 GeV. A comparison with a jet quenching model suggests that final state parton energy-loss dominates in central Cu+Cu collisions at 62.4 GeV and 200 GeV, while the enhancement at 22.4 GeV is consistent with nuclear modifications in the initial state alone.

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The measurement of particle yields at high transverse momentum ($p_T \gtrsim 2$ GeV/c) has played a key role in characterizing the medium created in nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) [1, 2]. Hadrons produced at sufficiently high p_T result from the interaction of quarks and gluons with high momentum transfer (“hard scattering”) which can be described by perturbative quantum-chromodynamics (pQCD). These hadrons are produced as particle jets in the fragmentation of the scattered partons. A scattered parton propagating through a quark-gluon plasma, a thermalized medium in which quarks and gluons are not confined in hadrons, loses energy (“jet-quenching”) resulting in hadron yields at high p_T being suppressed [3]. Such a suppression was indeed observed in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV at RHIC, providing evidence for large color-charge densities in these systems [4, 5, 6].

Characteristic properties of the suppression of hadrons at high- p_T , *e.g.*, the dependence on p_T and centrality, were studied in detail in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]. However, the energy dependence of hadron production in A+A collisions as predicted by jet quenching models [7, 8, 9] is not well constrained by measurements. Work in this direction was presented in [10, 11, 12]. To study the energy dependence of jet-quenching it is desirable to measure identified particles in the same colliding system over a large $\sqrt{s_{NN}}$ range and to compare to p+p reference data measured in the same experimental setup. Identified particles provide an advantage over unidentified hadrons in that the interpretation is not complicated by the different contributions from baryons and mesons. The study of Cu+Cu

collisions is particularly useful because hadron suppression in Au+Au collisions is observed for rather peripheral collisions with a number of participating nucleons of $N_{part} \sim 50 - 100$ [5]. This N_{part} range can be studied with reduced uncertainties in N_{coll} with the smaller ^{63}Cu nucleus.

A critical parameter in jet quenching models is the initial color-charge density of the medium. By studying Cu+Cu collisions in the range $\sqrt{s_{NN}} \sim 20 - 200$ GeV this parameter can be varied with essentially no change in transverse size and shape of the reaction zone. Moreover, the enhancement of hadron yields due to multiple soft scattering of the incoming partons (“nuclear k_T ” or “Cronin enhancement”) is expected to increase towards smaller $\sqrt{s_{NN}}$ [8], thus the interplay between this enhancement and the suppression due to parton energy-loss can be studied.

In this letter we present invariant π^0 yields for Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4$, and 200 GeV. Reference data for p+p collisions at $\sqrt{s} = 62.4$ GeV and 200 GeV were taken with the same experiment [13, 14]. At $\sqrt{s_{NN}} = 22.4$ GeV p+p reference data were obtained from a parameterization of the world’s data on π^0 production [15].

Neutral pions were measured via their $\pi^0 \rightarrow \gamma\gamma$ decay branch with the electromagnetic calorimeter (EMCal) of the PHENIX experiment [16]. The EMCal comprises two calorimeter types: 6 sectors of a lead scintillator sampling calorimeter (PbSc) and 2 sectors of a lead glass Cherenkov calorimeter (PbGl). Each sector is located ~ 5 m from the beamline and subtends $|\eta| < 0.35$ in pseudorapidity and $\Delta\varphi = 22.5^\circ$ in azimuth. Owing to the PbSc (PbGl) granularity of $\Delta\eta \times \Delta\varphi = 0.011 \times 0.011$

TABLE I: Data sets presented in this paper with the number of analyzed events. For the ERT triggered data the number of equivalent minimum bias events is given.

system	$\sqrt{s_{NN}}$	$\varepsilon_{\text{trig}}$	$N_{\text{evt}}^{\text{MB}}$	$N_{\text{evt}}^{\text{ERT}}$	$(N_{\text{evt}}^{\text{sampled}})$
Cu+Cu	22.4 GeV	75 – 90%	$5.8 \cdot 10^6$	—	—
Cu+Cu	62.4 GeV	$(88 \pm 4)\%$	$192 \cdot 10^6$	—	—
Cu+Cu	200 GeV	$(94 \pm 2)\%$	$794 \cdot 10^6$	$15.5 \cdot 10^6$	$(4720 \cdot 10^6)$

(0.008×0.008) the probability that the two photon showers from a π^0 decay result in partially overlapping clusters is negligible up to a π^0 p_T of 12 GeV/ c (15 GeV/ c). The energy calibration of the EMCal was corroborated by the position of the π^0 invariant mass peak, the energy deposited by minimum ionizing charged particles traversing the EMCal (PbSc), and the correlation between the measured momenta of electron and positron tracks identified by the ring-imaging Cherenkov detector and the associated energy deposited in the EMCal. These studies showed that the accuracy of the energy measurement was better than 1.5%.

The total number of analyzed Cu+Cu events for the three energies is shown in Table I. The minimum bias (MB) trigger for all reaction systems was provided by Beam-Beam-Counters (BBC's) located at $3.0 \lesssim |\eta| \lesssim 3.9$. The reaction vertex along the beam axis, determined from the arrival time differences in the BBC's, was required to be in the range $|z| \leq 30$ cm. An additional hardware trigger (ERT) on high- p_T photons/electrons was employed in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV. This trigger was based on the analog energy signal measured in overlapping 4×4 towers of the EMCal in coincidence with the MB trigger condition. The ERT reached a efficiency plateau for photon energies $E \gtrsim 4$ GeV.

The centrality selection in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 62$ GeV was based on the charge signal of the BBC's which is proportional to the charged particle multiplicity in the respective pseudorapidity range. The BBC trigger efficiency ($\varepsilon_{\text{trig}}$) for these systems was determined with the aid of the HIJING event generator and a full GEANT simulation of the BBC response (see Table I). At $\sqrt{s_{NN}} = 22.4$ GeV centrality classes were defined based on the charged particle multiplicity measured with the pad chamber (PC1) detector ($|\eta| < 0.35$). The measured PC1 multiplicity distribution was accurately reproduced in a Glauber Monte Carlo calculation [17] and centrality classes were determined by identical cuts on the measured and simulated PC1 multiplicities. The estimated BBC trigger efficiency given in Table I results from a comparison of the simulated and the measured PC1 multiplicity distributions. The results of the Glauber calculation [17] for Cu+Cu collisions at 22.4, 62.4, and 200 GeV using inelastic cross sections of 32.3, 35.6, and 42 mb, respectively, are given in Table II.

TABLE II: Glauber Monte Carlo calculations for Cu+Cu collisions at 22.4, 62.4, and 200 GeV. The N_{coll} systematic uncertainty at 62.4 and 200 GeV is $\sim 12\%$, almost independent of N_{coll} . At 22.4 GeV the relative uncertainty of N_{coll} can be parameterized as $0.094 + 0.173e^{-0.0272N_{\text{coll}}}$.

	22.4 GeV		62.4 GeV		200 GeV	
	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$
0-10 %	92.2	140.7	93.3	152.3	98.2	182.7
10-20 %	67.8	93.3	71.1	105.5	73.6	121.1
20-30 %	48.3	59.7	51.3	67.8	53.0	76.1
30-40 %	34.1	38.0	36.2	42.6	37.3	47.1
40-50 %	23.1	22.9	24.9	26.2	25.4	28.1
50-60 %	15.5	13.9	16.1	15.0	16.7	16.2
60-70 %	—	—	—	—	10.4	9.0
70-80 %	—	—	—	—	6.4	4.9
80-94 %	—	—	—	—	3.6	2.4
60-88 %	—	—	7.0	5.5	—	—

Neutral pions yields were measured on a statistical basis by calculating the invariant mass of all photon pairs in a given event and counting those within the π^0 mass range. The background of combinatorial pairs was calculated by pairing photon hits from different events. Only photon pairs with an energy asymmetry $|E_1 - E_2|/(E_1 + E_2) < 0.7$ were accepted. The raw π^0 yields were corrected for the geometrical acceptance and reconstruction efficiency. The latter takes into account the loss of π^0 's due to photon identification cuts, the energy asymmetry cut, inactive detector areas, and photon conversions. Moreover, it corrects the distortion of the π^0 spectrum which results from the finite energy resolution in conjunction with the steeply falling spectra and shower overlap effects. For Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV the transition between the minimum bias and the ERT sample occurs at $p_T = 8$ GeV/ c . The final spectra were calculated as the weighted average of the PbSc and PbGl results, which agree well within the uncertainties.

The main systematic uncertainties of the π^0 spectra result from the π^0 peak extraction, the reconstruction efficiency, and the EMCal energy calibration. For $p_T \gtrsim 2$ GeV/ c the peak extraction uncertainty is $\sim 4\%$ for all systems, approximately independent of p_T . The uncertainty in the reconstruction efficiency was estimated to be $\sim 15\%$ for the three Cu+Cu analyses. It includes uncertainties of the photon identification cuts, the energy resolution, and the modeling of shower overlap effects. The uncertainty in the EMCal energy scale of 1.5 % translates into an uncertainty in the yields that increases from $\sim 8\%$ at $p_T = 3$ GeV/ c to 15 % at $p_T = 6$ GeV/ c . The high- p_T part of the spectra in Cu+Cu at 200 GeV measured with the ERT trigger is subject to an additional uncertainty of 10 % related to the ERT trigger efficiency

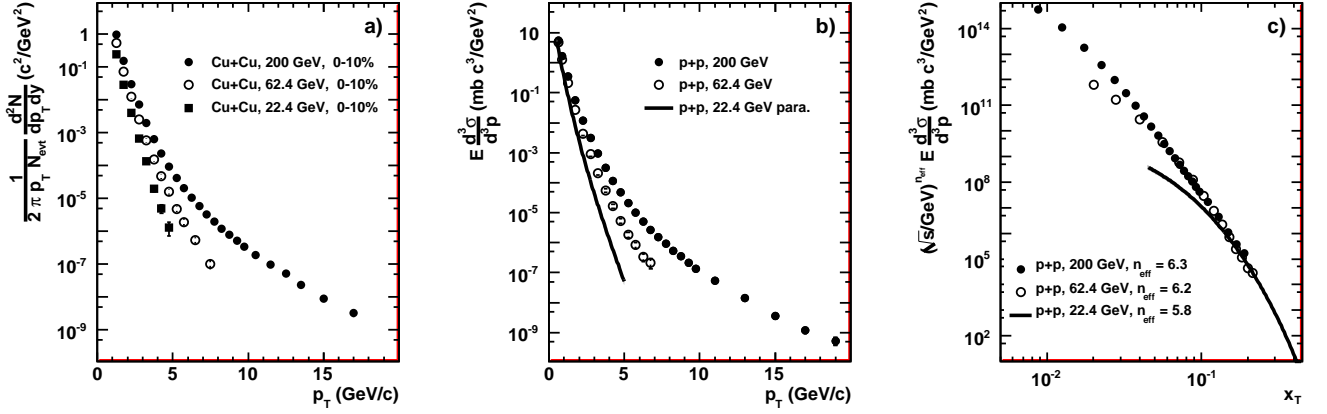


FIG. 1: Invariant π^0 yields in central Cu+Cu collisions (a) and invariant π^0 cross sections in p+p collisions (b) at $\sqrt{s_{NN}} = 22.4, 62.4, 200$ GeV [13, 14]. The error bars represent the quadratic sum of the statistical and total systematic uncertainties. Plotted as a function of $x_T = 2p_T/\sqrt{s}$ (c) the p+p data exhibit an approximate x_T scaling.

and normalization.

PHENIX has not yet acquired a p+p data set at $\sqrt{s} = 22.4$ GeV. Therefore world data on charged and neutral pion production in the range $21.7 \leq \sqrt{s} \leq 23.8$ GeV were scaled to $\sqrt{s} = 22.4$ GeV and fit in the range $0 \lesssim p_T \lesssim 7$ GeV/c with $E d^3\sigma/dp^3 = A(e^{ap_T+b})^n(\sqrt{s}/2 - p_T)^m$ where $A = 1.22 \cdot 10^{-17} \text{ mb GeV}^{-2} \text{ c}^3$, $a = 0.053 \text{ GeV}^{-1} \text{ c}$, $b = -0.884$, $n = -15.25$, and $m = 4.653$ [15]. The scaling correction was determined with a next-to-leading-order QCD calculation. The scaling correction was largest for $\sqrt{s} = 23.8$ GeV and reduced these spectra by $\sim 30\%$ [15]. The parameterization is consistent within $\pm 25\%$ with the existing π^0 and π^\pm measurements without discernible p_T -dependent systematic deviations.

The π^0 p_T spectra for p+p and central Cu+Cu collisions ($0-10\%$ of $\sigma_{inel}^{\text{Cu+Cu}}$) at $\sqrt{s_{NN}} = 22.4, 62.4$ [13], and 200 GeV [6] are shown in Fig. 1a and 1b. At sufficiently high p_T where pion production in p+p collisions is dominated by fragmentation of jets, QCD predicts a scaling law $\sqrt{s}^{n_{eff}(x_T, \sqrt{s})} E d^3\sigma/dp^3 = G(x_T)$ with a universal function $G(x_T)$ where $x_T = 2p_T/\sqrt{s}$ [18]. Fig. 1c shows that such a scaling in x_T is indeed observed for p+p collisions at 22.4, 62.4, and 200 GeV, consistent with previous observations [19]. The x_T values at which the universal curve $G(x_T)$ is reached indicate that particle production is dominated by hard processes for $p_T \gtrsim 2$ GeV/c for the three considered energies.

Nuclear effects on high- p_T π^0 production can be quantified with the nuclear modification factor

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{\text{evt}}) d^2 N_{AA}/dp_T dy}{\langle T_{AB} \rangle \times d^2 \sigma_{pp}/dp_T dy} \quad (1)$$

where $\langle T_{AB} \rangle = \langle N_{coll} \rangle / \sigma_{pp}^{\text{inel}}$. In the absence of nuclear effects $R_{AA} = 1$ for $p_T \gtrsim 2$ GeV/c where pions result from hard scattering processes. $R_{AA}(p_T)$ for the $0-10\%$ most central Cu+Cu collisions at 22.4, 62.4, and 200 GeV

is shown in Fig. 2. The suppression at 62.4 GeV ($R_{AA} \approx 0.6$ for $p_T \gtrsim 3$ GeV/c) and 200 GeV ($R_{AA} \approx 0.5-0.6$ for $p_T \gtrsim 3$ GeV/c) is consistent with expectations from parton energy-loss. The $R_{AA} > 1$ in Cu+Cu at 22.4 GeV is similar to the enhancement by a factor ~ 1.5 (at $p_T \approx 3$ GeV/c) observed in p+W relative to p+Be collisions at $\sqrt{s_{NN}} = 19.4$ GeV and 23.8 GeV [20]. For a similar number of participants the R_{AA} in Cu+Cu at 22.4 GeV agrees with the R_{AA} in Pb+Pb collisions at 17.3 GeV [12].

For $p_T \gtrsim 3$ GeV/c the measured nuclear modification factors at 62.4, and 200 GeV are consistent with a numerically evaluated parton energy-loss model described in [21, 22] as indicated by the comparison in Fig. 2. This calculation takes into account shadowing from coherent final state interactions in nuclei [23], Cronin enhancement [24], initial state parton energy-loss in cold nuclear matter [25], and final state parton energy-loss in dense partonic matter [9, 21, 22]. The Cronin enhancement measured in p+A collisions is described well by this model [24]. The initial gluon rapidity density dN^g/dy which characterizes the medium was not fit to the R_{AA} values, but instead was constrained by measured charged-particle multiplicities and the assumption of parton-hadron duality ($dN^g/dy = \kappa d\eta/dy dN_{ch}/d\eta$ with $\kappa = 3/2 \pm 30\%$ and $d\eta/dy \equiv 1.2$ at all energies) [21, 22]. The average fractional energy losses $\Delta E/E$ for a quark (gluon) with $E = 6$ GeV corresponding to the dN^g/dy ranges in Fig. 2 are $0.13-0.19$ ($0.29-0.42$), $0.16-0.20$ ($0.35-0.44$), $0.20-0.28$ ($0.44-0.63$) in central Cu+Cu collisions at 22.4, 62.4, and 200 GeV, respectively [22]. For Cu+Cu at $\sqrt{s_{NN}} = 22.4$ GeV the calculation is also shown without final state parton energy-loss. The measurement is consistent with this calculation but does not rule out a scenario with parton energy-loss.

Fig. 3 shows that the π^0 suppression in the range

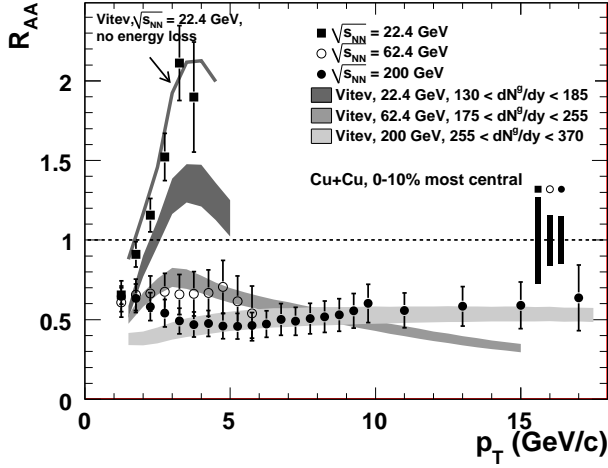


FIG. 2: Measured π^0 R_{AA} as a function of p_T for the 0–10% most central Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4, 200$ GeV in comparison to a jet quenching calculation [21, 22]. The error bars in this figure (and in Fig. 3) represent the quadratic sum of the statistical uncertainties and the point-to-point uncorrelated and correlated systematic uncertainties. The boxes around unity indicate uncertainties related to $\langle N_{coll} \rangle$ and absolute normalization. The bands for the theory calculation correspond to the assumed range of the initial gluon density dN^g/dy . The thin solid line is a calculation without parton energy-loss for central Cu+Cu at $\sqrt{s_{NN}} = 22.4$ GeV.

$2.5 < p_T < 3.5$ GeV/c increases towards more central Cu+Cu collisions for $\sqrt{s_{NN}} = 62.4, 200$ GeV. On the other hand, R_{AA} at $\sqrt{s_{NN}} = 22.4$ GeV remains approximately constant as a function of N_{part} , suggesting either that the Cronin enhancement depends only weakly on centrality or that in this energy range parton energy-loss is offset by the larger effect of Cronin enhancement over a broad range of centrality. It appears from these data that in Cu+Cu collisions between $\sqrt{s_{NN}} = 22.4$ and 62.4 GeV parton energy-loss will start to prevail over the Cronin enhancement, resulting in a net suppression.

In summary, for the first time π^0 p_T spectra for the same nuclear colliding system (Cu+Cu) were measured in the same experimental setup over a wide range of energies ($\sqrt{s_{NN}} = 22.4, 62.4$, and 200 GeV). Nuclear effects were studied using measured p+p π^0 reference spectra from PHENIX at 62.4 and 200 GeV, and a parameterization of world data at 22.4 GeV. High- p_T π^0 yields in central Cu+Cu collisions at 62.4 GeV and 200 GeV are suppressed, suggesting that parton energy-loss is a significant effect in these systems. At 22.4 GeV π^0 yields for $p_T \gtrsim 2$ GeV/c are not suppressed. The R_{AA} measured in central Cu+Cu at 22.4 GeV is consistent with Cronin enhancement alone but does not rule out parton energy-loss effects. The measurements of high- p_T π^0 production over a factor ~ 10 in center-of-mass energy presented in this letter provide a unique constraint for jet-quenching models and demonstrate that parton energy-loss starts to pre-

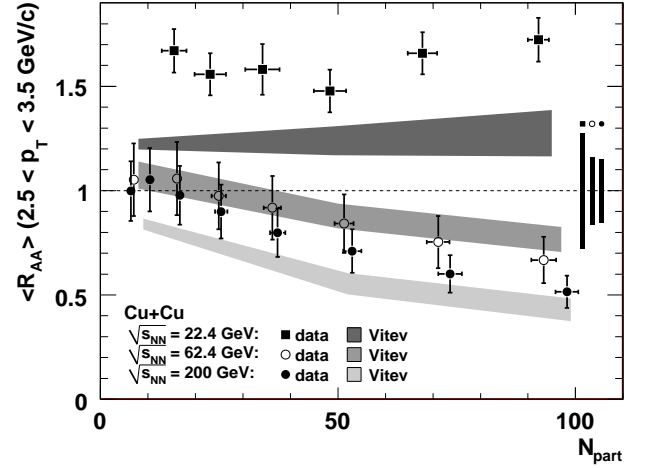


FIG. 3: The average R_{AA} in the interval $2.5 < p_T < 3.5$ GeV/c as a function of centrality for Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4, 62.4$, and 200 GeV. The shaded bands represent jet quenching calculations at three discrete centralities ($N_{part} \sim 10, 50, 100$) [21, 22]. The boxes around unity represent the normalization and $\langle N_{coll} \rangle$ uncertainties for a typical N_{coll} uncertainty of 12%.

vail over the Cronin enhancement between $\sqrt{s_{NN}} = 22.4$ and 62.4 GeV.

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